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Wind energy feasibility study for city of Shahrbabak in Iran

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ABSTRACT

Climate change, global warming, and the recent worldwide economic crisis have emphasized the need for low carbon emissions while also ensuring economic feasibility. In this paper, the status and wind power potential of the city of Shahrbabak in Kerman province in Iran was investigated. The technical and economical feasibility of wind turbine installation is presented. The potential of wind power generation was statistically analyzed. The mean wind speed data of three-hour interval long term period from 1997 to 2005 was adopted and analyzed in order to determine the potential of wind power generation. The numerical values of the dimensionless Weibull shape parameter (k) and Weibull scale parameter (c) were determined. Annual values of "k" ranged from 1.725 to 1.930 with a mean value of 1.504, while annual values of "c" were in the range of 4.848–6.095 with a mean value of 5.314 (m/s). With the average wind power density of 100 W/m^2, it is found that the city is not an appropriate place for construction of large-scale wind power plants, but is suitable for employment of off-grid electrical and mechanical wind driven systems. An economic evaluation was done in order to show feasibility of installing small wind turbines. It was concluded that it costs 18 cents for 1 kW h which is 5 cents more than the market price. Each turbine of 10 kW can supply power for icebox, washer, water pump, TV, lighting, electrical fan, charger, and air conditioning units for small houses. In order to utilize wind energy in the region, it is recommended to install small size wind turbines for electricity supply of public and public buildings and private houses.

Contents

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1. Introduction

Wind presents an attractive source of renewable energy employment in many countries in the world [1]. It is well known that fossil fuels have limited resources and at current rates of exploitation they are expected to deplete within the next centuries. This is one of the reasons why clean, sustainable and environmentally friendly alternative energy resources are currently sought. The accumulation of carbon dioxide in the lower layers of the atmosphere gives way to climate change, floods, intensive rainfalls and droughts. In order to reduce these dangerous effects, it is the responsibility of each country to improve the quality of the energy resources, and if possible, to replace fossil fuels (coal and oil) with renewable energy alternatives such as wind, solar and other energy sources [2]. The positive effects of renewable energies have forced scientists to draw attention to clean energy sources which are both environmentally more suitable and renewable.

The positive impacts of wind energy on the mitigation of climate change as well as opportunity to diminish energy dependency are indisputable. Wind energy helps decreasing import dependency, diversifying sources of production, and contributes to a sustainable development in many countries [1]. Iran enjoys high wind energy potential, but exploitation and investigation of this clean renewable source is still below the desired level.

The density of air decreases with increase in temperature. Thus, lighter air from the equator rises up into the atmosphere to a certain altitude and then spreads around. This causes a pressure drop around this region, which attracts the cooler air from the poles to the equator. This movement of air causes the wind. Thus, the wind is generated due to the pressure gradient resulting from the uneven heating of earth's surface by the sun. As the very driving force causing this movement is derived from the sun, wind energy is basically an indirect form of solar energy [3].

Growth in the wind energy sector has recently been most phenomenal among other renewable sources of energy. Consensus exists almost worldwide that for ensuring sustainable development, wind energy can definitely play an important role. Wind energy is one of the oldest sources of energy used by human being, comparable only to the use of animal force and biomass. Ancient cultures, dating back to several thousand years, took advantage of wind energy to propel their sailing vessels. There are references to windmills relating to a Persian windmill in 644 AD and to windmills in Persia in 915 AD. These early wind energy converters were essential for pumping water and grinding cereals [4]. Up to the year 2008, the top five countries in terms of installed wind turbine capacity are the USA, Germany, Spain, China, and India [4]. One of the solutions for reducing the problems related to fast depleting fossil fuel resources, climate change and environmental crises is to utilize different kinds of renewable energies, including geothermal, hydraulic power, wind power, biomass, solar heat and power, etc.

Global population is increasing day by day. The population growth is more rapid in developing countries than the industrialized nations [5]. As a result of this population growth, increasing the standards of living and developmental activities, the energy demand is also increasing [3].

The most significant advantage of wind energy is that it does not pollute the atmosphere with toxic chemicals. In contrast, the conventional power plants operating on fossil fuels release toxic gases during the energy conversion process. The maximum global wind potential is almost 35% of the total world energy consumption. The energy potential of the wind is an important source of clean energy which is available in many parts of the world as well as in Iran. Feasibility study of wind energy production in some parts of Iran has been done. Abundant wind resources are mainly distributed in Manjil and Binalood areas in North of Iran.

This paper presents research work involved in determining the feasibility of deploying wind driven devices in the city of Shahrbabak, thereby reducing green house gas emissions, costs and utilizing a renewable natural energy resource.

The next section offers a discussion of wind resource assessment for Iran in general. In Section 3, the site considered in this study which is the city of Shahrbabak in central part of Iran is described. The review analysis procedures and discussion on the results are presented in Sections 4 and 5 respectively. The economic evaluation is brought forward in Section 6, and finally concluding remarks are presented in Section 7.

2. Wind resource assessment for Iran

Iran is located in the western part of South-West Asia. Its land area is 1,648,195 km^2. This country faces climate variability. Northern parts of Iran have moderate climates with considerable rainfall, especially in western regions of Gilan Province. Western parts are cold and humid in cold season, dry and mild during warm seasons. In southern parts, air temperature and humidity is normally high, encountering very hot summers and mild winters. East and southeast regions have a desert climate with significant variations in temperature throughout the day.

The strongest and most persistent winds (Jet Stream) blow at an altitude of 10 km from ground level. While heights of wind turbines are limited to 150 m, wind velocity is influenced by surface friction and thus the wind speed is less than the higher elevations. Altitude of less than 1000 m is called boundary layer. The feature of boundary layer is such that the wind velocity is zero at the ground level and monotonically increases as height is increased. Estimation of wind energy in complex areas requires computer simulation and modeling, while wind data for an area should be used. Iran has two mountain ranges of Alborz and Zagros which are located between flows in the main air route between Asia, Europe, Africa, Indian Ocean and the Atlantic Ocean. The main purpose of preparing a wind atlas is to identify and evaluate suitable areas for implementing wind energy projects and construction of wind power plant.

Iran (Persia) is situated in south-western Asia and borders the three CIS states, the Republic of Armenia, the Republic of Azerbaijan, and the Republic of Turkmenistan, as well as the Caspian Sea to the north, Turkey and Iraq to the west, the Persian Gulf and the Gulf of Oman to the south, Pakistan and Afghanistan to the east [6]. Clearly, contribution of the wind energy for production of electricity in Iran is very low. Its share is 0.04% which is almost negligible. But there are many suitable locations, which could be considered as wind farms in different parts of Iran for that purpose. Unfortunately, because of the low price of oil and gas in Iran, most of the electricity has been produced by fossil fuel in the past. There is a great concern towards renewable energies in Iran like wind and solar ones. As a result, Iranian government has put all its effort to expand wind and solar farms in different parts of Iran.

Wind energy potential of Iran is estimated to be about 6500 MW. Most of the developed countries with similar wind energy potential to Iran are taking advantage of this phenomenon energy at an accelerating rate. Presently, more than 23 billion kW h of

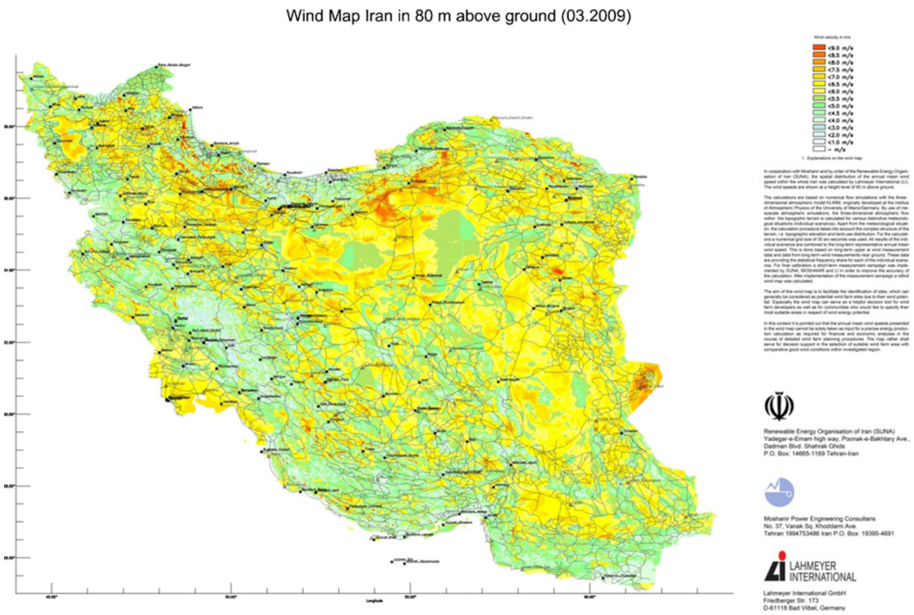

Fig. 1. Wind atlas of Iran for elevation of 80 m above the ground [19].

cheap and clean electricity are being produced annually across the globe. India power production utilizing wind energy is estimated around1000 MW. Germany produced some 4400 MW of electricity with wind. While Iran has a comparable level of available wind power, produces only 10 MW [7,8].

First successful experience in installing and utilizing modern wind turbines in Iran dates back to 1994. Two sets of 500 kW Nordtank wind turbines were installed in Manjil and Roodbar. They produced more than 1.8 million kW h per year. These two sites are located 250 km from Tehran. The average wind speed is 15 m/s for the period of 3700 h/year in Roodbar, and 13 m/s for the period of 3400 h/year in Manjil. After this successful experience, in 1996 the contract for 27 wind turbines was signed and they were installed by 1999 in Manjil, Roodbar and Harzevil. Harzevil is the third wind farm site near to Manjil. Manjil is about 800 m above sea level and Harzevil is about 500 m higher. There are 21 installed wind turbines in Manjil, 1 with 500 kW, 5 with 550 kW and 15 with 300 kW capacities [8,9]. Abundant wind resources are mainly distributed in Manjil and Binalood areas in northern part of the country. Generally the resource potential of wind in Manjil and Binalood is excellent. Sites of good or excellent resource potential, with the wind power density above 400 W/m^2 or even reach 800 W/m^2, and wind speed more than 7.0 m/s, are suitable candidates to locate the wind power plants.

Manjil is situated about 220 km north-east of Teheran and 80 km south of the Caspian Sea in the province of Gilan. Its wind conditions are characterized by average wind speeds of about 6 m/s (at 40 m above the ground level) in winter and by superb wind conditions especially in summer. The strong north-wind in the months from May to September with an average wind speed of 14 m/s (at 40 m above ground level) and more can be explained with the local climatic and geographic circumstances [10]. This is an excellent location because the electricity production from wind turbine is very high.

On a large scale, the latitude and physical geography including the proportion of land and sea, size of landmasses, presence of mountains or plains, altogether determine the wind resources distribution. More locally, the topography has a major effect on the wind climate [11,12].

Wind energy potential assessment of Iran has been done for numerous locations such as Semnan [8] Manjil [6], Yazd [13] and Tehran [14]. There are also studies about feasibility of offshore wind turbine installation in Iran and comparison with the rest of the world [15], future of renewable energies in Iran [16] and renewable energy issues in Middle East compared with Iran [17]. The present study is devoted to shows the status and feasibility of wind energy potential in city of Shahrbabak which is located in Kerman province in Iran.

3. Description of the location

Shahrbabak is an ancient city in Iran. Historians believe this town has built by Ardeshir Babakan the most famous Sasanian king around 1800 years ago. It is located in province of Kerman in southern part of Iran. Meymand, one of the 4 oldest villages in Iran is 36 km far from Shahrbabak. Sarcheshmeh and Miedook, the biggest copper mines in Iran, are also located around this town. It is located in the west part of the Kerman Province. To its east is Rafsanjan, in its southern limits is Sirjan, and to the north and west has common borders with the province of Yazd. Geographers have mentioned this city in their records, and others have related its historical past with that of Kerman [18]. Wind data for the site under consideration was obtained from Iranian Meteorological Organization. At the beginning of this feasibility study, some assumptions were made, and then the actual analysis was done. It was initially assumed that the city is a good location in order to harness wind energy for commercial purposes. Then actual data were collected and wind power density was calculated in order to evaluate and discuss our assumption. Fig. 1 shows wind atlas of Iran for 80 m above the ground [19]. Population density map of Iran (Fig. 2) shows that city of Shahrbabak is not populated [14]. Also, location of Shahrbabak is shown in Fig. 3 [20].

4. Analysis procedure

In order to accurately evaluate the wind energy potential of the region and clarify its characteristics, it is required to carry out long-term meteorological observations for the location under consideration. Clearly, wind speed is a random variable, and probability density functions could be calculated from analyzing the variation of wind speed over a period of time.

Fig. 2. Map of population density for Iran [14].

Wind speed frequency distribution has been represented by different probability density functions such as Weibull Rayleigh, three parameter beta, lognormal, and gamma distributions. Weibull distribution is one of the most commonly used methods for determining wind energy potential.

4.1. Weibull probability density function

The use of Weibull distribution requires that the shape factor k and the scale factor c should be initially determined, for which adequate field data collected at shorter intervals of time are necessary [21]. The wind speed distribution predominantly determines the performance of wind power systems. Knowing the wind speed distribution, the wind power potential and, hence, the economic viability could be easily obtained There are different density functions that can be used to describe the wind speed frequency curve. Here, the Weibull distribution is used to describe the wind speed distribution. Probability density function for wind speed is calculated from Eq. (10) [22–26]:

Fig. 3. Map of Kerman province showing the city of Shahrbabak [20].

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e\left(-\left(\frac{v}{c}\right)^{k}\right) \quad (k > 0, v > 0, c > 1) \tag{1}$$

where $f(v)$ is the wind speed probability for speed v, c is the Weibull scale parameter, and k is the shape parameter. When the average speed and variance of the data is calculated, the following scale and shape parameters could be attained [22]. The Weibull parameters k, resemble the wind potential of the location and indicates how peaked the wind distribution is.

$$k = 0.83v^{0.5} \tag{2}$$

The scale parameter, c, indicates how 'windy' a wind location under consideration is, Once the mean speed, and the variance of the data are known, the following approximation can be used to calculate the Weibull parameters c [14]:

$$c = \frac{v}{\Gamma(1 + (1/k))} \tag{3}$$

Maximum likelihood method can also be used to calculate the shape parameter k and the scale parameter c. The equations for k and c are as follows [21]:

$$K = \left[\frac{\sum_{i=1}^{n} V_i^k Ln(V_i)}{\sum_{i=1}^{n} V_i^k} - \frac{\sum_{i=1}^{n} V_i^k Ln(V_i)^{-1}}{n}\right] \tag{4}$$

$$C = \left(\frac{1}{n}\sum_{i=1}^{n} V_i^K\right)^{1/K} \tag{5}$$

But for this study Eqs. (2) and (3) were used. The parameter $\bar{v}$ is the average wind speed which can be calculated as follows:

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{6}$$

σ^2 is the variance for wind velocity recordings which can be calculated as follows:

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{v})^2 \tag{7}$$

Average wind speed and the variance of wind velocity can be calculated on the basis of the Weibull parameters as follows [14,27]:

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{8}$$

$$\sigma^2 = c^2\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{2}{k}\right)\right] \tag{9}$$

The gamma (Γ) function of (x) (standard formula) is also calculated as follows:

$$\Gamma_{(x)} = \int_0^{\infty} e^{-u} u^{x-1}\, du \tag{10}$$

In circumstances where k is equal to 2, the Weibull distribution is referred to as Rayleigh distribution. The manufacturers often provide standard performance using this special case of the Weibull distribution [14,28]. The main limitation of the Weibull density function is that it does not accurately represent the probabilities of observing zero or very low wind speeds [14,29]. However, for the purpose of estimating wind potential for the commercial use of

wind turbines, this is usually unnecessary as the energies available at low wind speeds are negligible (i.e. wind energy is proportional to the cube of wind velocity) and below the operating range of wind turbines (i.e. the cut-in wind speed is usually between 2.5 and 3.5 m/s [14,30]).

4.2. Wind power density

Wind turbines are designed with a cut-in speed, or the wind speed at which it begins to produce power, and a cut-out speed, or the wind speed at which the turbine will be shut down to prevent its failure. Usually, the range of cut-in wind speed is 3.0–4.5 m/s, and the cut-out speed can be as high as 25 m/s. Hence, the probability of wind speed exceeding 25 m/s is negligible for Shahrbabak.

Wind power that flows at speed v through a blade sweep area A, increases with the cube of the wind speed and the areas:

$$P(v) = \frac{1}{2}\rho A v^2 \tag{11}$$

ρ is density of air at sea level with a mean temperature of 15 °C and a pressure of 1 atm (1.225 kg/m^3) and v is the mean wind speed (m/s). Then the corrected monthly air density ρ (kg/m^3) is calculated as follows [14,31]:

$$\rho = \frac{\bar{p}}{R_d \bar{T}} \tag{12}$$

where $\bar{T}$ is average monthly air temperature in Kelvin (K); $\bar{p}$ is the average of monthly air pressure in Pascal (Pa), and R_d is gas constant for dry air which its value is 287 J/kg K. It is important to mention that most of the available units of pressure are provided in H-Pascal (1H-Pascal = 100 Pa).

We could also calculate the corrected available power at elevation of 10 m above the ground as follows [14,32]:

$$P_{10} = \frac{1}{2}\rho A v_{10}^3 \left(\frac{w}{m^2}\right) \tag{13}$$

Calculation of the monthly corrected and uncorrected wind power revealed that the corrected air density values are almost stable. Also, the shift from the standard air density (ρ = 1.225kg/m^3) is very small for the selected region, consequently the latter value was considered in the present study. The density of air decreases with the increase in site elevation and temperature. The air density may be taken as 1.225 for most of the practical cases. Due to this relatively low density, wind is rather a diffused source of energy.

Estimation of wind power is based on the assumption that the density of air is not correlated with wind speed. The error introduced by this assumption on a constant pressure surface is less than 5% [14,33,34].

Wind power density, expressed in Watt per square meter (W/m^2), takes into account the frequency distribution of the wind speed and the dependence of wind power on air density and the cube of the wind speed. Therefore, wind power density is generally considered a better indicator of the wind energy resource than wind speed [14,35]. The average wind power density is calculated as:

$$WPD = \frac{\sum_{i=1}^{n} 1/2\rho v_i^2}{N} \tag{14}$$

If we denote i as the measured three-hourly wind speed and N be the total sample wind speed data for each year. Wind power density can be developed by Weibull distribution analysis by using formula (15).

In order to evaluate available wind resource at a site, it is required to calculate the wind power density. It shows how much energy is available at the site for conversion to electricity by a wind turbine. The wind power per unit area, P/A or wind power density can be calculated as following [8,36]:

$$\frac{P}{A} = \int_0^{\infty} \frac{1}{2}\rho v^2 f(v)\, dv = \frac{1}{2}\Gamma \rho c^3 \left(1 + \frac{3}{k}\right) \tag{15}$$

4.3. Wind energy density

Wind energy density for a desired duration can be calculated as:

$$\frac{E}{A} = \left(\frac{P}{A}\right) n\,\Delta t = \frac{1}{2}\Gamma \rho c^3 \left(1 + \frac{3}{k}\right) n\,\Delta t \tag{16}$$

where n is the number of measurement periods, Δt. According to Keyhani et al. [14] "This equation can be used to calculate the available wind energy for any defined period of time when the wind speed frequency distributions are for a different period of time. The Betz limit, which has been commonly used now for decades, gives that a wind turbine would not extract more than 59.3% of the available wind power. Therefore, the maximum extractable power from the wind will be the product of the factor 0.593 and the calculated result from Eq. (15)."

4.4. Most probable wind speed

The most probable wind speed (V_{mp}) and the optimal wind speed carrying maximum energy can be calculated from k and c values. The most probable wind speed (V_{mp}) shows the most frequent wind speed for a given wind probability distribution:

$$V_{mp} = c\left(1 - \frac{1}{k}\right)^{1/k} (\mathrm{m/s}) \tag{17}$$

4.5. Optimal wind speed

Jamil et al. [27] mentioned that "wind speed carrying maximum energy represents wind speed which carries maximum wind energy". Optimal wind speed (v_{op}) can be expressed as following formula:

$$v_{op} = c\left(1 + \frac{2}{k}\right)^{1/k} (\mathrm{m/s}) \tag{18}$$

In some references this is expressed as the optimum wind speed for a wind turbine, v_{op}, which is the speed that produces the most energy [14,26]. The wind turbine should be chosen with a rated wind speed that matches this maximum energy wind speed for maximizing energy output. Once v_{op} is obtained for one site, the optimal rated wind speed of a wind turbine can be found (the rated velocity of a turbine is the lowest wind velocity corresponding to its rated power that due to technical and economical reasons, the wind turbine is designed to produce constant power, termed as the rated power). For the annual energy output, the chosen wind turbine will have the highest capacity factor, defined by the ratio of the actual power generated to the rated power output [14,37].

5. Results and discussion

In this study, wind speed data for city of Shahrbabak, over a nine-year period from 1997 to 2005 were analyzed. Calculations were then made to obtain the Weibull distribution parameters in terms of c and k, mean wind speed and measured and predicted mean wind power. Following is the main results obtained from this study.

5.1. Monthly mean wind speeds

The monthly mean wind speed values v and standard deviations σ are presented in Table 1 for Shahrbabak, 1997–2005. The trends

Table 1
Yearly wind speeds and standard deviations for city of Shahrbabak.

Month	Parameter	1997	1998	1999	2000	2001	2002	2003	2004	2005	Whole year
January	$\bar{v}$	3.936	4.226	2.343	4.698	2.621	4.730	3.956	4.577	4.343	3.936
	σ	2.351	4.713	4.414	5.079	4.137	5.291	5.113	4.949	5.955	4.826
February	$\bar{v}$	0.214	5.732	3.388	4.578	4.487	5.281	5.817	4.806	5.196	4.391
	σ	1.349	6.422	4.388	5.610	5.563	5.318	5.935	5.930	5.766	5.575
March	$\bar{v}$	6.210	5.492	4.565	5.560	4.177	5.250	6.077	4.984	6.375	5.410
	σ	5.931	6.344	5.552	6.505	4.743	5.585	6.647	5.916	6.439	6.021
April	$\bar{v}$	5.575	5.929	4.996	3.817	4.171	4.971	5.033	4.833	5.075	4.933
	σ	5.963	5.975	6.342	5.212	4.609	5.391	5.517	5.611	5.296	5.589
May	$\bar{v}$	4.726	5.448	4.778	3.282	4.794	4.778	6.105	5.141	5.480	4.948
	σ	5.174	5.885	5.678	4.090	5.573	5.475	6.111	5.873	5.657	5.568
June	$\bar{v}$	5.904	5.900	4.292	4.983	4.950	5.467	4.771	5.167	5.154	5.176
	σ	6.193	5.081	4.332	4.617	4.958	5.796	5.285	5.104	4.558	5.148
July	$\bar{v}$	5.915	6.996	6.500	8.020	7.294	5.685	6.690	7.544	5.931	6.731
	σ	5.083	5.531	6.432	5.603	5.468	4.856	5.547	5.502	4.639	5.472
August	$\bar{v}$	7.387	7.419	6.835	7.621	7.117	6.980	7.331	6.637	5.593	6.991
	σ	5.613	5.255	5.478	5.761	5.405	4.356	5.718	5.662	4.772	5.375
September	$\bar{v}$	4.417	3.554	4.304	3.929	4.079	4.554	4.313	6.117	4.492	4.418
	σ	4.594	4.297	4.383	4.410	4.302	4.619	5.313	4.920	4.726	4.669
October	$\bar{v}$	3.645	2.621	3.492	2.435	3.407	3.234	6.597	3.956	3.347	3.304
	σ	4.301	4.446	4.034	3.784	4.972	3.895	4.594	4.683	3.416	4.279
November	$\bar{v}$	2.771	1.442	3.854	2.008	3.463	2.942	3.288	4.717	3.696	3.131
	σ	3.906	3.046	5.015	3.469	4.744	3.872	4.333	4.921	4.311	4.320
December	$\bar{v}$	2.806	1.194	2.427	3.234	2.806	4.597	3.560	6.327	2.427	3.264
	σ	3.872	2.728	3.517	4.093	4.028	5.160	5.115	5.395	3.843	4.487
Yearly	$\bar{v}$	4.492	4.659	4.321	4.523	4.450	4.873	5.046	5.406	4.757	4.725
	σ	5.093	5.460	5.212	5.238	5.094	5.098	5.610	5.469	5.130	5.279

of the monthly means for the different years are similar. Most of the monthly mean speed wind values are between 4 and 5 m/s, but some are over 5.50, while only a few are over 7 m/s and under 2.50 m/s.

Most of the average wind speeds are in the range between 4 and 5 m per second with a frequency of approximately 30.5%. Remaining frequency data is as follows: greater than 6 m/s (20.3%), between 3 and 4 m/s (19.4%), between 5 and 6 m/s (17.5%), and more than 3 m/s (12.03%). In the period studied, the mean maximum wind speed belongs to July 2000 amounts to 8.020 m/s and the minimum wind speed of 0.214 m/s is for Feb 1997. It could be concluded that the monthly wind speed distribution has a significant difference.

July 2000 showed the maximum mean wind speed value with 8.02 m/s, and February 1997 showed the lowest mean wind speed value of 0.214 m/s. By analyzing the 108 months of collected wind speed data, it can be concluded that the wind speed distribution differs remarkably from one month to the next. The monthly and yearly standard deviation values are between 1.349 and 6.647 m/s for February 1997 and March 2003 respectively. The monthly mean wind speeds (1997–2005) are illustrated in Figs. 4 and 5.

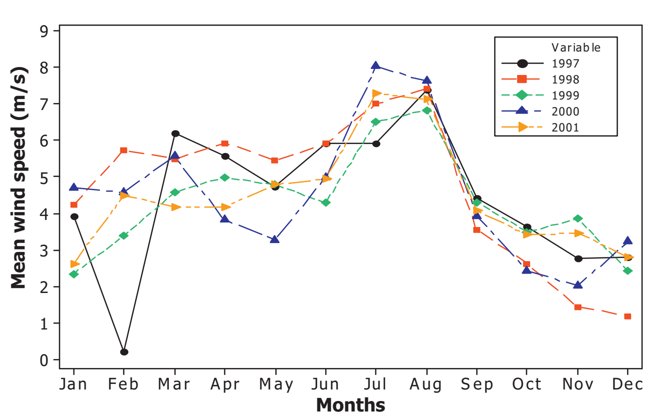

Fig. 4. Monthly mean wind speed 1997–2001.

Figs. 4 and 5 show that the whole year wind speed has the lowest value in the month of November and the highest in the month of August, ranging from 3.131 to 6.991 m/s with an annual average of 4.725 m/s. The higher heating demand in Shahrbabak occurs from December to March, which can be grouped as the cold season. It is possible that wind energy could be applied as a supplement to the current gas or electricity heating, but more information is required for this purpose. From April to November is the warm season in Shahrbabak. For the cold season, the nine-year overall mean wind speed is 4.176 m/s. Also, for warm season, the nine-year overall mean wind speed is 5.266 m/s. Table 2 shows that the mean wind speeds in the warm season are higher than those in the cold season.

For the purpose of calculating seasonal mean wind speeds, the months in each of the four seasons in the northern hemisphere are generally divided as follows: (a) winter: December, January and February; (b) spring: March, April and May; (c) summer: June, July and August and (d) autumn: September, October and November.

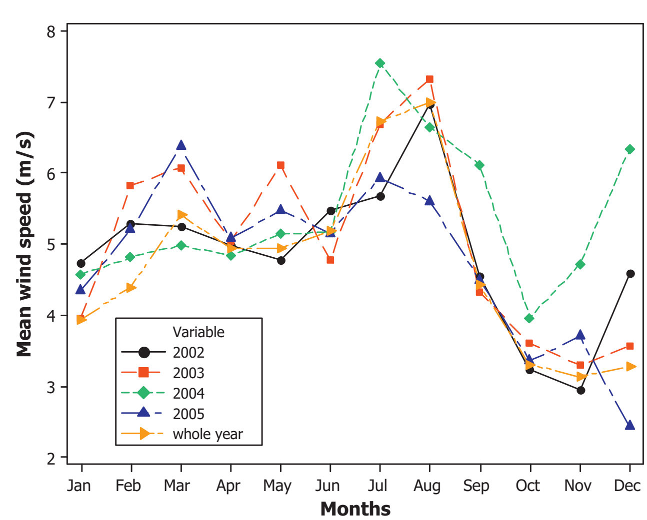

Fig. 5. Monthly mean wind speed 2002–2005.

Table 2
Yearly mean wind speed variation (in m/s) for cold season (November–April) and warm season (May–October) based on nine-year data (1997–2005).

Year	Cold season	Warm season
1997	3.634	5.334
1998	3.978	5.329
1999	3.590	5.041
2000	3.988	5.051
2001	3.604	5.282
2002	4.625	5.118
2003	4.607	5.478
2004	5.046	5.762
2005	4.509	5.001
Whole year	4.176	5.266

5.2. Annual and overall mean wind speeds

The yearly mean wind speeds can be obtained by averaging all the available wind speed in the year for Shahrbabak. The average values for each year from 1997 to 2005 and the overall nine-year average are listed in Table 3.

Results show that all mean wind speeds of Shahrbabak are lower than 5.4 m/s and the yearly mean wind speed values range from 4.322 to 5.406 m/s. The highest mean wind speed occurs in 2004 with value of 5.406 m/s, but the lowest belongs to 1999 which is 4.322 m/s. According to the PNNL (Pacific Northwest National Laboratory) classification system [14], Shahrbabak falls outside of the range based upon the yearly mean wind speed. This means that, under the current wind turbine technique, this area may not be suitable for year round large-scale electricity generation due to the cost factor. However for small-scale applications, and in the long run with the development of wind turbine technology, the utilization of wind energy is still promising. Average k value from 1997 to 2005 is 1.804, and c value for same period is 5.314 m/s.

5.3. Diurnal wind speed variations

The diurnal wind speed variations are illustrated in Figs. 6 and 7. Clearly, maximum wind speed occurs at noon for all nine years. It can be found that the daytime is windy for all years, while the night time is relatively very calm. The wind speed increase at around 3 a.m. and the peaks at around 12 noon. After that, the afternoons are characterized by decreasing wind speeds. If we decide to use wind energy for street lighting, hence, it has to be stored for night time. During night, the wind speed is at its lowest value. If the energy demand is higher in the day time, wind turbines could operate more economically.

Table 3
Yearly Weibull parameters and characteristic speeds (at 10 m height, in m/s) for the years studied in Shahrbabak.

Year	k	c (m/s)	V_{mp}	v_{op}	$\bar{v}$ (measured)
1997	1.759	5.045	3.128	7.768	4.492
1998	1.792	5.238	3.320	7.959	4.659
1999	1.725	4.848	2.934	7.574	4.322
2000	1.765	5.080	3.164	7.804	4.523
2001	1.751	4.997	3.081	7.721	4.450
2002	1.832	5.484	3.565	8.204	4.873
2003	1.864	5.683	3.763	8.401	5.046
2004	1.930	6.095	4.175	8.81	5.406
2005	1.810	5.351	3.432	8.072	4.757
Whole year	1.804	5.314	3.396	8.035	4.725

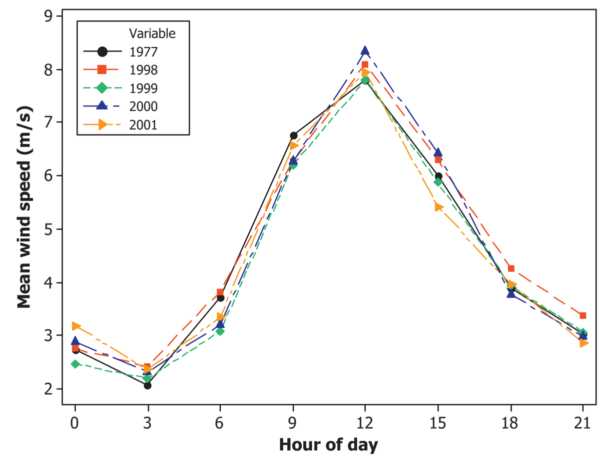

Fig. 6. Diurnal variation of wind speed for city of Shahrbabak, 1997–2001.

5.4. Weibull distribution

The Weibull distribution may vary from site to site, both in its shape, and in its median value. There are two parameters that govern the shape of the Weibull distribution curve, namely, the scale parameter c (m/s) and the shape parameter k (dimensionless), calculated from the long term wind data for the site studied. A higher value of the scale parameter means the distribution is spread over a wider range and the probabilistic average wind velocity has a higher value. A higher value of shape parameter (between 2 and 3) means the distribution is more skewed towards higher wind velocities, if the shape parameter is between 1 and 2, it means that the distribution is skewed towards lower velocities, indicating a higher probability of lower wind velocities. Of course, both these parameters influence the peak distribution curve, but one has major influence on the average value and the other primarily influences the skewness of the curve. For an exact feeling of curve, both values should be considered together. If the shape parameter is exactly 2, the distribution is known as a Rayleigh distribution. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution [4].

The annual values of the scale parameter c (m/s) and shape parameter k (dimensionless) are presented in Table 3 which were calculated from nine years period (1997–2005) wind data for the city of Shahrbabak. Formulas in Section 4.1 were used for calcu-

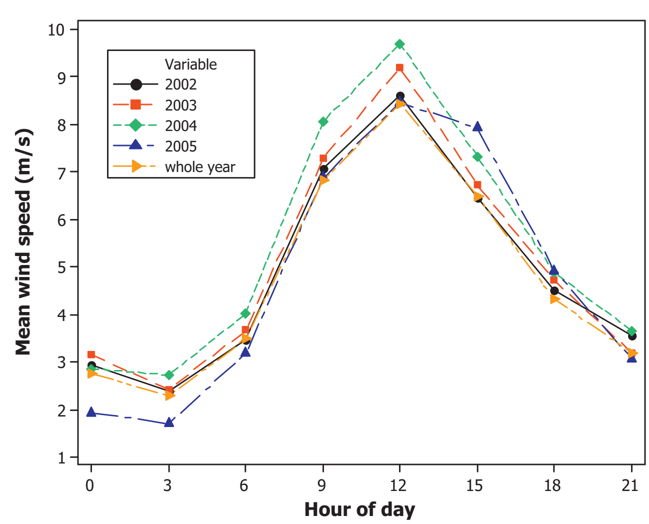

Fig. 7. Diurnal variation of wind speed for city of Shahrbabak, 2002–2005.

Table 4
Monthly Weibull parameters and characteristic speeds (at 10 m height, in m/s) and wind power density and energy for whole year for city of Shahrbabak.

Month	k	c (m/s)	V_{mp}	v_{op}	$\bar{v}$ (measured)	P/A (W/m^2)	E/A (kW h/m^2/Month)
January	1.647	4.401	2.495	7.133	3.936	74.8	53.86
February	1.740	4.929	3.014	7.654	4.391	96.1	69.19
March	1.931	6.100	4.180	8.815	5.410	157.1	113.11
April	1.844	5.550	3.634	8.273	4.933	123.0	88.56
May	1.846	5.570	3.651	8.290	4.948	121.5	87.48
June	1.889	5.832	3.912	8.550	5.176	133.0	95.76
July	2.153	7.600	5.687	10.311	6.731	254.3	183.10
August	2.195	7.893	5.983	10.605	6.991	282.4	203.33
September	1.745	4.960	3.044	7.684	4.418	91.9	66.168
October	1.509	3.662	1.781	6.408	3.304	47.9	34.49
November	1.469	3.459	1.589	6.210	3.131	43.5	31.32
December	1.500	3.616	1.737	6.363	3.264	48.4	34.85

lation of k and c values. Clearly, k value is without unit, but unit for c value is m/s. It is obvious that the parameter k has a much smaller, temporal variation than the parameter c. Values of k are all less than 2. Annual values of k range between 1.725 and 1.930 with an average value of 1.804. The minimum value of k is found in 1999, but the maximum belongs to 2004. The minimum value of c is 4.848 m/s and is found in year 1999, while the highest value is 6.095, which occurred in the year 2004. The average value of c is 5.314 for the study period.

In this study, monthly Weibull parameters of k and c were calculated (Table 4). Clearly, the monthly wind speed distribution (1997–2005) differs over a whole year. Values of c are mostly less than 8. Annual values of c range between 3.459 and 7.893. The minimum value of c is found in November, but the maximum belongs to August.

5.5. Wind power density and energy calculation

It is well known that the wind power that flows at speed v through a blade sweep area A increases as the cube of its velocity and is given by [22]. The power of wind and energy density (Table 7) are calculated by Eqs. (15) and (16).

For city of Shahrbabak, the highest value of wind power density was in 2004 with value of 153.5 (W/m^2) followed by 2003 with 129.5 (W/m^2) and 2002 with amount of 119.1 (W/m^2). The minimum was found to be 89.1 (W/m^2) in 1999. The energy values for the city range between 780.516 and 1344.66 kW h/m^2/year. Average annual amount of energy for nine years period (1997–2005) was 968.856 kW h/m^2/year.

A classification [8,36] indicated the wind characteristics and evaluations as following:

$$\begin{aligned} &\frac{\bar{P}}{A} < 100\,\mathrm{W/m^2} \quad \text{is poor}\\ &\frac{P}{A} \approx 400\,\mathrm{W/m^2} \quad \text{is good}\\ &\frac{P}{A} > 700\,\mathrm{W/m^2} \quad \text{is great} \end{aligned} \tag{19}$$

Based upon the above classification, the Shahrbabak city is almost a poor location.

A classification done by European Wind Energy Association (EWEA), the wind characteristics and categories are indicated as below [39]:

fairly good (6.5 m/s, ≈300–400 W/m^2);
good (7.5 m/s, ≈500–600 W/m^2);
very good (8.5 m/s, ≈700–800 W/m^2).

According to the above classification, Shahrbabak is not a favorable location for wind turbine installation. Also, the following classification shows that the city is categorized as fairly good.

Table 5
Wind power classifications for 50 m elevation [12].

Wind power class	Potential	Wind power density (W/m^2)	Wind speed (m/s)[a]
1	Poor	0–200	0.0–5.6
2	Marginal	200–300	5.6–6.4
3	Moderate	300–400	6.4–7.0
4	Good	400–500	7.0–7.5
5	Excellent	500–600	7.5–8.0
6	Excellent	600–800	8.0–8.8
7	Excellent	More than 800	More than 8.8

[a] Wind speeds are based on Weibull k value of 2.0.

Another classification done based on the wind energy densities is as [40];

fair (P, W/m^2 < 100);
fairly good (100 ≤ P, W/m^2 < 300);
good (300 ≤ P, W/m^2 < 700);
very good (P, W/m^2 ≥ 700).

Yu and Qu [12] noted that sites of good or excellent resource potential, with the wind power density above 400 W/m^2 or even reach 800 W/m^2, and wind speed more than 7.0 m/s, are suitable candidates to locate the wind power plants (Table 5).

Parvin [41] used the classifications (Table 6) for 10 m height. Shahrbabak is placed in class 2 (Table 6). Possible power generation with a grade average wind speed through the wind turbine technology does not exist today. Thus, with advances in wind turbine technology in the coming years Shahrbabak wind farm construction is susceptible. The city is not suitable for large-scale electric wind application. But, small-scale wind turbines could be good option for Shahrbabak in order to supply power for lightings, electric fans, and chargers (Table 7).

Clearly, big monthly changes in the wind power density were found with a maximum value (282.4 W/m^2 in August) being 6.49 times of the minimum (43.5 W/m^2 in November).

The significant monthly change underscores the importance of distinguishing different months of the year when a wind power

Table 6
Wind power classifications for 10 m elevation.

Wind class	Min wind speed (m/s)	Max wind speed (m/s)	Min wind power density (W/m^2)	Max wind power density (W/m^2)
1	0	4.4	0	100
2	4.4	5.1	100	150
3	5.1	5.6	150	200
4	5.6	6.0	200	250
5	6.0	6.4	250	300
6	6.4	7.0	300	400
7	7.0	9.4	400	1000

Table 7
Weibull wind power and annual energy production for different years (1997–2005) for Shahrbabak.

Year	P/A (W/m^2)	E/A (kW h/m^2/year)
1997	97.9	857.604
1998	106.7	934.692
1999	89.1	780.516
2000	99.4	870.744
2001	95.4	835.704
2002	119.1	1043.316
2003	129.5	1134.42
2004	153.5	1344.66
2005	113.3	992.508
AVG yearly	110.6	968.856

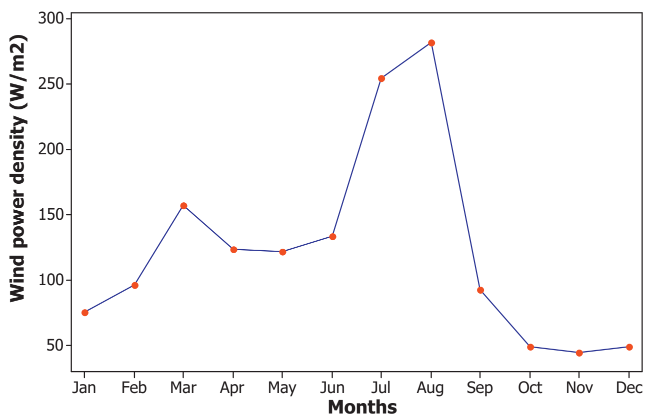

Fig. 8. Monthly variation of the wind power density for whole year (1997–2005).

project is assessed or designed [14]. The results of data from Fig. 8 and Table 4 were revealed in Table 8 which is about the wind power densities in Shahrbabak. Results from table reveal that by decreasing wind speeds from August, July, March and June (6.991, 6.731, 5.410, and 5.176 m/s); hence, wind power densities would also decrease respectively (282.4, 254.3, 157.1 and 133.0). But there is oddness about months of April and May. Month of May with higher mean wind speed (4.948 m/s) has lower power density than April (4.933 m/s).

Table 8
Wind power density, wind speed and standard deviation for months of 1997–2005.

Month	Parameter	Whole year wind speed (m/s)	Wind power density (W/m^2)
January	$\bar{v}$	3.936	74.8
	σ	4.826	
February	$\bar{v}$	4.391	96.1
	σ	5.575	
March	$\bar{v}$	5.410	157.1
	σ	6.021	
April	$\bar{v}$	4.933	123.0
	σ	5.589	
May	$\bar{v}$	4.948	121.5
	σ	5.568	
June	$\bar{v}$	5.176	133.0
	σ	5.148	
July	$\bar{v}$	6.731	254.3
	σ	5.472	
August	$\bar{v}$	6.991	282.4
	σ	5.375	
September	$\bar{v}$	4.418	91.9
	σ	4.669	
October	$\bar{v}$	3.304	47.9
	σ	4.279	
November	$\bar{v}$	3.131	43.5
	σ	4.320	
December	$\bar{v}$	3.264	48.4
	σ	4.487	

Table 9
Detailed product description for a regular10 kW wind turbine.

	Main parameter	Unit
1	Rated power	10 kW
2	Rated rotated speed	160
3	Rated wind speed	11 m/s
4	Blade diameter	8.0 m
5	Max power	12 kW
6	Output voltage	240 V/380 V
7	Start up wind speed	3 m/s
8	Operating wind speed	3–25 m/s
9	Security wind speed	40 m/s
10	Height of tower	12 m
11	Weight of top section	600 kg
12	Output controller system	Charger and inverter
13	Tower pole type	Guy wired
14	Battery	12V200AH 40 pcs

This can be accounted for by difference in their standard deviations of the wind speed distributions in these months. The standard deviation in May is lower than April.

"With a higher standard deviation but lower mean wind speed, a higher wind power density is possible because the wind power density expressed by Eq. (15) monotonically increases with the standard deviation when the mean wind speed is given. In fact, a month with the same mean wind speed but higher standard deviation will have more potential to experience higher wind speeds, and the wind power density is proportional to the cube of the wind speed, so more wind power may be harnessed in such occasions [14]". From Table 4, regarding the power density values of different months, August and July devote the greatest values with 282.4 and 254.3 W/m^2, respectively.

"Since no existing wind machine can completely convert all of the output power to usable form, the Betz relation [42] assigns a power coefficient of 0.593 for the maximum extractable power from an optimum wind energy conversion system [14]".

Hence, maximum power extractable is found to be as: $0.593 \times 282.4\,\text{W/m}^2 \times A$ (swept area of the wind turbine) in August. Monthly energy density values (Table 4) are between 31.32 and 203.33 kW h/m^2/month. Table 7 shows maximum wind energy of 1344.66 (kW h/m^2/year) and minimum of 780.516 (kW h/m^2/year).

5.6. Wind turbine energy production

If we denote $P(v)$ as wind power that flows at speed v, and $Pw(v)$ as machine power curve, the average wind machine Power of $\overline{Pw}$ can be calculated as follows [43]:

$$\overline{Pw} = \int_0^{\infty} Pw(v)9(v)\,dv \tag{20}$$

In the following, a horizontal axis wind turbine model is used to find amount of energy which could harness. The wind turbine characteristics presented by the manufacture company is in Table 9. The model is selected based on height of tower, and wind potential of the city.

6. Economic evaluation

Economic issues of wind energy systems are multidimensional. There are several factors that affect the unit cost of electricity produced by a wind turbine. These may vary from country to country and region to region. Economic merit of a wind powered generation plant heavily depends on the local conditions. For a wind turbine,

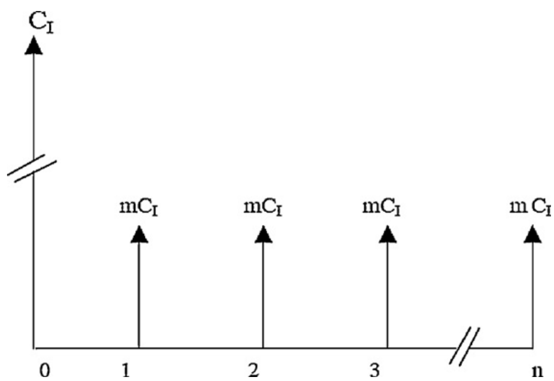

Fig. 9. Wind energy cost for a project.

the fuel is free, but the capital investment is high. While assessing the initial investment for the project, apart from the cost of the wind turbine, investment for other essential requirements like land, transmission lines, power conditioning systems, etc. should also be accounted [3].

The costs for a commercial scale wind turbine in 2007 ranged from \$1.2 million to \$2.6 million, per MW of nameplate capacity installed. Most of the commercial-scale turbines installed today are 2 MW in size and cost roughly \$3.5 million installed. Wind turbines have significant economies of scale. Smaller farm or residential scale turbines cost less overall, but are more expensive per kilowatt of energy producing capacity. Wind turbines under 100 kW cost roughly \$3,000 to \$5,000/kW of capacity. That means a 10 kW machine (the size needed to power an average home) might cost \$35,000–\$50,000 [44]. Gearboxes are still the Achilles' heel for the wind industry, and can cost up to \$500,000 to fix due to the high cost of replacement parts, cranes (which can cost \$75,000-\$100,000), post installation testing, re-commissioning and lost power production. Data analyzed in 'The Wind Energy Operations & maintenance Report' suggest that average operations and maintenance (O&M) costs run at approximately \$0.027/kW h or €0.019/kW h. This may sound like a small investment, but profitable wind farms require operators to run a tight ship. The report quotes an operator saying "Just a 1% improvement in O&M makes a huge difference on the bottom line" [38].

Mathew [3] discussed that "Insurance and taxes are the other expenses being incurred annually. The project has many costly and sensitive components, which are to be insured against unforeseen accidents and calamities. The insurance agencies have a wide variety of plans to suit the needs of their customers. Here also, local enquiry will help us to choose the right one for the project. Wind energy projects are partially or fully exempted from taxes in many countries. The level of exemption depends on the local tax laws. If the land required for the project is rented, it can be included in the operation and maintenance cost. Salaries of the project staff are another expenditure coming under the operation and maintenance head. Considering all these factors, it is a usual practice to consider the operation and maintenance charges as a fraction of the capital cost of the system. It is logical to assign 1.5–2% of the system cost for yearly repair and maintenance."

Annual costs involved in a wind energy project over its life span of n years are shown in Fig. 9 as follows:

Let C_I be the initial investment of the project and COM be the operation and maintenance cost including Salary, Insurance, Tax, Rent, and salvage value. Expressing the COM as a percentage m of C_I,

$$C_{OM} = mC_I \tag{21}$$

Now, discounting the operation and maintenance costs for n years to the initial year,

$$PW(C_{OM})_{1-n} = mC_I \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \tag{22}$$

Including the initial investment C_I, the accumulated net present worth of all costs is as following:

$$NPW(C_A)_{1-n} = C_I \left\langle 1 + m \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \right\rangle \tag{23}$$

Therefore, yearly cost of operation for the turbine is:

$$NPW(C_A) = \frac{NPW(C_A)_{1-n}}{n} = \frac{C_I}{n} \left\langle 1 + m \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \right\rangle \tag{24}$$

If P_R is the rated power of the turbine, and CF is the capacity factor, the energy generated (E_I) by the turbine in a year is:

$$E_I = 8760 \times P_R \times CF \tag{25}$$

Thus, the cost of kW h wind-generated electricity is given by:

$$C = \frac{NPW(C_A)}{E_I} = \frac{C_I}{8760n} \left(\frac{1}{P_R CF} \right) \left\langle 1 + m \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \right\rangle \tag{26}$$

For the annual energy output, the chosen wind turbine will have the highest capacity factor, defined by the ratio of the actual power generated to the rated power output [37]. The capacity factor can be calculated for one year having the annual power production of the wind turbine divided by the annual full power generation at rated power.

$$\text{Capacity factor} = \frac{P\,\text{MW h}}{(365\ \text{days}) \times (24\ \text{h/day}) \times (10\,\text{kW}) \times 1\,\text{MW}/1000\,\text{kW})} \tag{27}$$

Cost of an on grid 10 kW Evolve wind turbine is \$30,090. We assume other initial costs including installation, transportation, custom fee and grid integration are 40% of the turbine cost. Useful life of the system is 15 years. Annual operation and maintenance costs plus the land rent come to 6% of the turbine cost. Calculation for cost of generating electricity from the two turbines if to be installed in a residential house in Shahrbabak with capacity factor of 0.63 would be as follows:

The real rate of interest may be taken as 17%. Here, the installation cost of the turbines is:

$$2 \times 30,090 \times \frac{40}{100} = \$24,072$$

So, the total initial investment for the project is 60,180 + 24,072 = \$84,252. Therefore, cost of 1 kW h of electricity would be:

$$C = \frac{84,252}{8760 \times 15} \left(\frac{1}{10 \times 0.63} \right) \left\langle 1 + 0.06 \left[\frac{(1+0.17)^{15} - 1}{0.17} \right] \right\rangle = 0.18\,\$/\text{kW h} \tag{28}$$

At present, individual wind turbine owners at Manjil and Binalood areas in north of Iran are selling electricity at the rate of 0.13\$/kW h to government. Based upon the above calculations, it costs 18 cents for 1 kW h which is 5 cents more than the market price. Each turbine of 10 kW (Table 9) can supply power for Ice-box, washer, water pump, TV, lighting, electric fan, charger, and air condition for small houses. As shown in Fig. 10, it can obtain up to 2000 W energy while wind speed is 12 m/s. For average wind speed of 4.725 m/s for Shahrbabak, a 10 kW turbine could produce almost

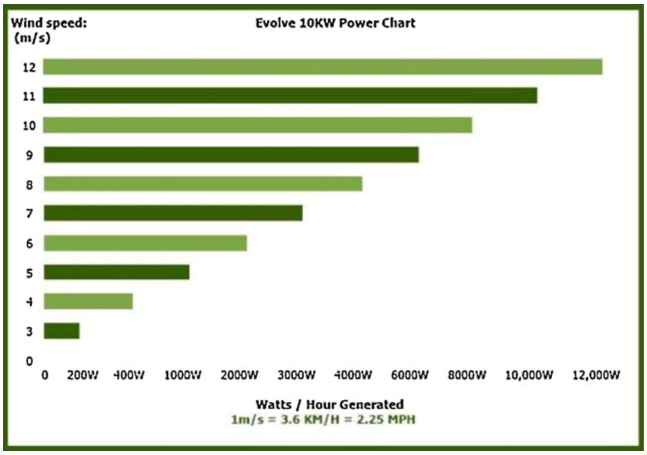

Fig. 10. Power chart for 10 kW wind turbine.

1000 W which is enough for supplying power for some house appliances.

7. Conclusions

With detailed planning for the future, drastic reductions in the fossil fuel consumption can be achieved by implementing the correct technologies. Wind turbine technology is one of the most favorable options which decision makers should consider for providing the clean energy for different purposes. Iran has undoubtedly significant potential for harnessing wind energy in many locations. In the present study, hourly measured long term wind speed data of Shahrbabak have been statistically analyzed. The probability density distributions have been derived from long term wind speed data and the distributional parameters were identified. As the yearly average wind power density value of 110.6 W/m^2 indicates, this site corresponds to wind power class 2, since the power density value is a little more than 100 W/m^2. Therefore, this particular site is not ideal for grid connected applications. This level of power density may be adequate for non-connected electrical and mechanical applications, such as wind generators, battery charging and water pumping. Because of low level of power density, the city presents poor wind characteristics. This is shown by the low monthly and yearly mean wind speed and power density values for the whole year. An economic evaluation was done in order to show feasibility of installing small wind turbines. It was concluded that it costs 18 cents for 1 kW h which is 5 cents more than the market price. Each turbine of 10 kW (Table 9) can supply power for Icebox, washer, water pump, TV, lighting, electric fan, charger, and air condition for small houses. It is recommended to install small size wind turbines for electricity production of the houses. This study indicates that small wind turbine projects at the Shahrbabak site are feasible.

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